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EFFECT OF DIE SLEEVE MATERIAL ON MECHANICAL BEHAVIOR OF A413 ALUMINIUM ALLOY PROCESSED THROUGH SQUEEZE CASTING ROUTE

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ABSTRACT

Squeeze casting as liquid-metal forging process by which molten metal solidifies under pressure within closed dies positioned between the plates of a hydraulic unit. The main objective of this work is to investigate the mold, metal of molten metal contact during solidification with different controlled input variables such as squeeze pressure, die preheating temperature and melt temperature for different die sleeve materials. Absolute process variables produce a rapid heat transfer rate that yields a pore-free fine-grain casting with good mechanical behavior. In the cast samples, the mechanical behavior such as hardness and ultimate tensile strength were measured. From the work, it was ascertained that castings produced by copper die, sleeve have good mechanical behavior due to the faster solidification rate for this route.

KEYWORDS: A413, Die sleeve Material, Squeeze Casting & Mechanical Behavior

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Original Article

INTRODUCTION

The automobile industries are focusing their concentration towards lightweight vehicles due to market demand and governing regulation. Weight reduction in vehicles can be achieved by the new engineering design and application of lightweight materials such as aluminum alloys and magnesium alloys. Among the lightweight materials, a large amount of castings is made from Al-Si alloy. These alloys are popularly used in aerospace, automobile, marine, and mining industries due to excellent properties [1]. The silicon-based aluminum alloy LM6, which was chosen for this work, is associated with the theoretical density of 2.66 g/cm^3. This alloy has been selected because of its good fluidity as well as the presence of silicon and magnesium. Since the silicon content of this alloy is sufficiently high, it can be maintained in the liquid state at typical casting temperatures for a certain period of time. Also, it is associated with excellent pressure tightness, good hot tear resistance, good castability, good machinability, high specific strength and high corrosion resistance. Due to these properties, it finds use in numerous places such as engine cylinder, piston, manifolds, motor casings etc.[1-4]. The conventional casting processes cannot achieve the defect-free castings and desirable properties that satisfy the current demand.

Squeeze casting is one of the modern casting techniques that respond best to the current demand. It is a hybrid metal casting process, in which the molten metal solidifies under pressure within the die cavity. Squeeze-cast products have superior properties over the conventional castings [5-6]. Squeeze pressure variation plays a major role in the formation of finer microstructure leading to good mechanical behavior. Further, higher pressure decreases the percentage of porosity and increases the density of the cast alloy [7-8]. In typical die casting process, an air gap is formed between mold to metal interfaces, which reduce the heat transfer coefficient, whereas, in squeeze casting the applied pressure greatly reduces the air gap and accelerates the cooling rate. This increases the heat transfer coefficient, thus producing pore-free grains [9]. The pressure range 171-210 MPa can be applied to achieve fine microstructure [10]. Further increasing of applied pressure cannot refine grains again.[11]. In squeeze casting process, effective process parameters accompanied by a specific pouring temperature give a fine microstructure with high density accompanied with elevated mechanical properties [12]. The lower die temperature less than 150°C causes low fluidity, thermal fatigue failures in the dies and cold lapse on the surface of the casting whereas higher die temperature greater than 400°C leads to the hotspot and shrinkage porosity in the castings [13]. It is believed that there is a critical pouring temperature between 700°C and 725°C which plays an important role to change the grain size [14]. Die sleeve material determines the heat transfer rate of the solidification process, which is a key factor in determining the desired properties of the castings [15-17]. Researchers found that in a casting using copper as a chill, with cooling by a phase-transition medium is a potential method for fast solidification, is resulting in good mechanical and tribological behavior [18]. Antecedent research works annotated that the hardness and ultimate tensile strength of A413 alloy with various process parameters of squeeze casting route had exhibited considerable improvement in mechanical properties as enumerated in Table 1. Among several casting techniques, squeeze casting showed better results due to the application of squeeze pressure. However, detailed mechanical and metallurgical property evaluation of A413 alloy with squeeze casting route for varying squeeze pressure, die preheating temperature and melt temperature for different diesleeve materials like copper, die steel, cast iron, and stainless steel had not been reported in the scientific community. The inquisition is enumerated and presented.

EXPERIMENTAL TECHNIQUE

Experimental Setup for A413 Castings Fabrication

The metallic H13 die steel die having provision to insert die sleeves made up of copper, cast iron, stainless steel and die steel, was firmly seated over the hydraulic unit base plates. The punch was firmly fitted with a hydraulic unit to apply the required squeeze pressure, to the capacity of 250 MPa (50 ton). The die pre-heater with the maximum range of 500°C capacity has thermocouple arrangements to control the temperature of the die accurately. A bottom pouring red-hot electric furnace maximum range of 1200°C with 2-liter capacity has been used to melt the metal. A preheated pathway unit, up to 600°C capacity is inbuilt in this setup. The entire squeeze casting setup is shown in Figure 1.

The experimentation was carried out by varying the influencing input parameters such as squeeze pressure, die preheating temperature and melt temperature. 1kg of A413 alloy was melted in this setup up to the parametric range. A cover flux of 8g is used to clean the melt, and standard hexachloroethane (C_2Cl_6) degasser was used to remove the entrapped gases. The squeezing pressure was applied to the molten metal by lowering the hot die steel punch which is attached to the hydraulic unit with varying Squeeze Pressure (70, 105 and 140 MPa), Die preheating temperatures (150°C, 225°C and 300°C) and Melt temperatures (650°C, 725°C and 800°C) respectively. The castings were fabricated

as per the DOE approach using (L27) FFD. The molten metal from the bottom pouring furnace was transferred into the preheated colloidal graphite coated H13 hot die steel with different die sleeves like copper, cast iron, die steel and stainless steel (it is shown in Figure 2) through preheated pathway within few seconds, so as to avoid melt temperature loss and turbulence of molten metal flow. After pouring molten metal, the compression loads were applied at a delay time of about five seconds and retained over the solidifying molten metal for 60 seconds to produce sound castings (diameter 50 mm x height 200 mm) and the Figure 3. show the samples prepared through die with the sleeve. Thermocouples were inserted into sleeve material, die and molten metal to measure the temperatures during solidification.

Specimen Preparation

A413 Castings for Hardness Test & Ultimate Tensile Test

Cast samples were machined to the testing conditions and for each type of test, three specimens were prepared. For the Brinell hardness (BHN) test, 250 kg load was applied for 10 to 15 seconds through a ball indenture of 10 mm on the polished specimen surface, and hardness values were measured in three spots of the cast specimen areas. The universal testing machine was employed in performing the tensile test on the specimens. Three tensile test specimens were prepared as per the E8M-04ASTM standard. From the tensile test conducted the Ultimate Tensile Strength (UTS) and Yield Strength (YS) readings for all the specimens were noted for each set. The average value is taken for further processing.

A413 Castings for Microscopy

For microscopic examination, specimens of cast samples measuring about 15 mm in diameter and 10 mm in thickness were first grinded through emery papers and then polished by 6-micrometer diamond paste. The cast samples were then etched with Keller's reagent to obtain a better contrast (1.0 ml HF, 2.5ml HNO3, 1.5 ml HClF, 95.0 ml Water) and dried by an electric dryer. Grain boundaries were observed with a metallurgical microscope having a 100X magnification. All the specimens were prepared as per the E3-01ASTM standard and response was measured.

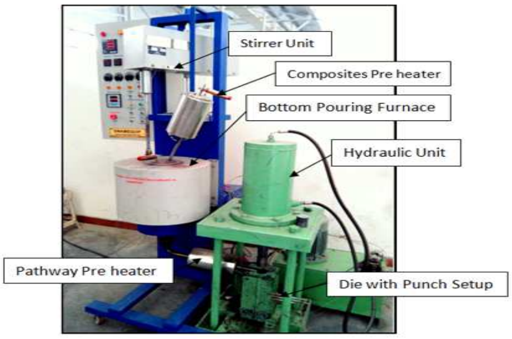


Figure 1: Squeeze casting Setup

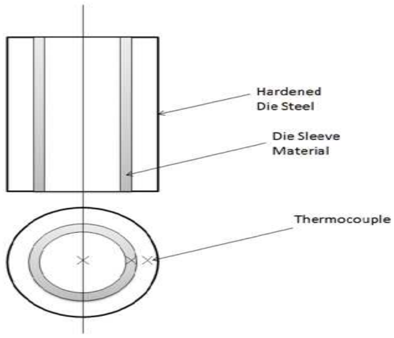


Figure 2: Arrangement of Die and Sleeve

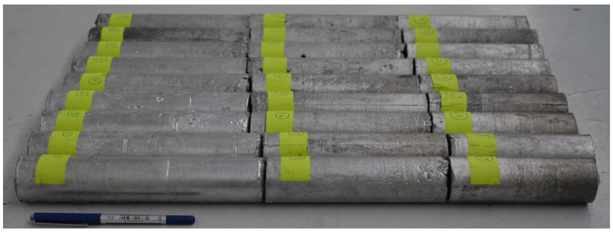


Figure 3: Squeeze Casted Prepared Samples

RESULTS AND DISCUSSIONS

The influential parameters were squeezed under pressure, die preheating temperature, molten metal temperature and die sleeve material. Among them, the first three parameters are varied according to FFD during experimentation for each die, sleeve material and their results are shown in Table 1.

Table 1: Assigned Orthogonal L27 with the Acquired Data for Different Die Sleeve Materials

S. No	Squeeze Pressure in MPa	Die Preheating Temp in °C	Melt Temp in °C	Copper		Cast Iron		Stainless Steel		Die Steel	
				Hardness in BHN	UTS in MPa	Hardness in BHN	UTS in MPa	Hardness in BHN	UTS in MPa	Hardness in BHN	UTS in Mpa
1	70	150	650	75	312	74	270	70	231	72	252
2	70	225	650	80	321	79	291	72	242	76	266
3	70	300	650	69	296	66	240	62	220	65	236
4	70	150	725	75	318	73	272	69	235	71	249
5	70	225	725	82	331	81	310	75	248	78	269
6	70	300	725	69	303	67	249	64	224	66	237
7	70	150	800	76	309	74	281	70	231	72	239
8	70	225	800	79	312	79	300	73	235	75	248
9	70	300	800	68	294	63	235	56	212	62	232
10	105	150	650	85	320	84	297	78	265	84	285
11	105	225	650	89	331	88	312	81	272	87	289
12	105	300	650	82	289	78	275	73	257	79	258
13	105	150	725	90	339	88	303	80	268	89	284
14	105	225	725	92	346	90	335	83	277	88	293
15	105	300	725	84	312	82	298	76	260	81	274
16	105	150	800	84	321	83	291	78	263	78	265
17	105	225	800	90	334	89	319	82	276	87	291
18	105	300	800	81	289	79	268	69	235	79	258
19	140	150	650	87	341	93	324	81	287	94	298
20	140	225	650	89	346	94	335	84	292	92	299
21	140	300	650	84	312	89	304	73	279	87	286
22	140	150	725	94	353	95	331	82	286	94	301
23	140	225	725	98	360	97	348	85	294	95	305
24	140	300	725	88	312	89	302	76	278	87	287
25	140	150	800	92	324	91	314	80	287	91	285
26	140	225	800	95	341	94	339	84	293	92	299
27	140	300	800	83	310	84	293	70	266	83	284

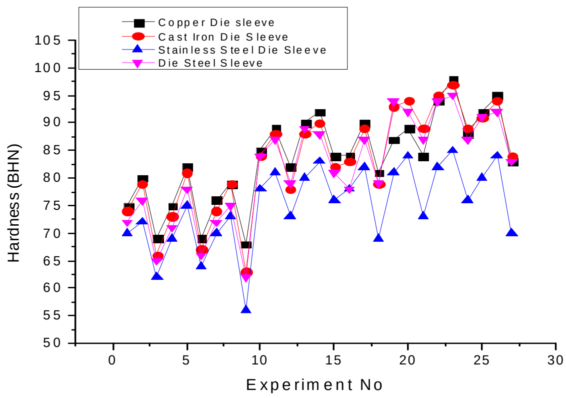


Figure 4: Comparison of Hardness for different dies

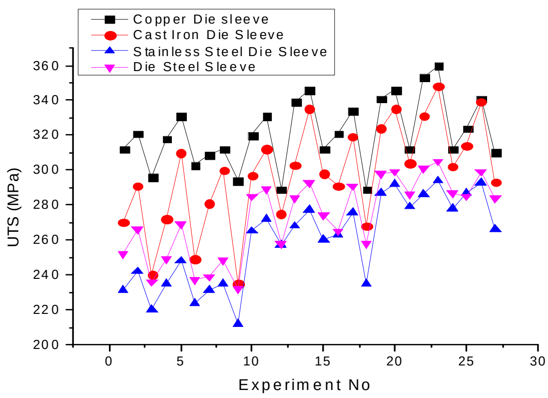


Figure 5: Comparison of UTS for different dies

Effect of Squeeze Casting Process Parameters

The effect of squeeze casting parameter for a die, sleeve material on the output responses is discussed below. During the solidification of the casting process, an air gap is formed between the metal – mold interface which is found to have a major influence on the properties of casting. The air gap reduces the value of heat transfer coefficient, in the interface region, resulting in prolonged solidification time. In squeeze casting process, the applied squeeze pressure reduces the air gap and decreases the solidification time. It is observed that the maximum results were obtained from the

squeeze pressure of 140 MPa. With a maximum pressure of 140 MPa, undercooling in the melt is higher than the lower squeeze pressures. This larger amount of undercooling stimulates more existing nuclei in the melt to start spontaneous heterogeneous solidification. As a result, much-refined microstructure will be obtained at 140 MPa than the ones, that processed under lower pressures of 70 and 105 MPa. In this volume and shape of the castings, applied pressure of 140 MPa provides higher cooling rate coupled with large undercooling. The scientific theory for obtaining maximum squeeze pressure will accelerate the solidification process leading to the formation of fine grain dendritic structure as compared to slow cooling in lesser pressure levels. Maximum squeeze pressure decreases the percentage of porosity and increases the density, resulting in high hardness and UTS. Further increase of applied pressure above 140 MPa has no significant effect on the dendritic structure as well as improvement in mechanical properties.

Die preheating temperature and melt temperature has a predominant effect on the solidification rate of the casting. By reducing the value of T_d (Die Preheating Temperature), a faster cooling rate can be obtained resulting in a fine grain structure. But the lower die temperature of 150ºC causes premature solidification, incomplete die fillings, thermal fatigue failures, cold laps in casting and poor surface roughness. The higher die preheating temperature of 300ºC, cause hot spots and shrinkage pores in the casting, cooling rate was comparatively lower, and the amount of undercooling was insufficient due to the gentler temperature gradient resulting in the formation of large dendrites. Hence better mechanical properties were obtained for the die preheating temperature of 225ºC.

According to the equation governing the heat transfer, there should be a higher heat transfer for high melting temperature, but it leads to the formation of the large dendritic structure due to solidification delay. The high melt temperature of 800ºC cause shrinkage porosity and effect the die life. Whereas lower melt temperature of 650ºC leads to incomplete die filling, inadequate fluidity, cold laps and premature solidification in the castings. Hence melt temperature of 725ºC was optimum and leads to higher mechanical properties. From the Figure 4 &5, higher hardness and UTS was attained for the squeeze pressure of 140 MPa, die preheating temperature of 225 ºC and melt temperature of 725 ºC.

Effect of Die Sleeve Material

To investigate the effect of die, sleeve material, the squeeze pressure was varied while the die preheating temperature and melt temperature was fixed. The minimum solidification time was observed during the experimentation using a copper die sleeve. The scientific theory for obtaining better results for copper die, sleeve material is as follows. Different materials have a different thermal conductivity which has a great influence on the heat transfer during solidification. The governing equation for heat transfer is given by, $Q = h (T_c - T_d)$ Where: Q - heat flux across the casting/die interface, h - heat transfer coefficient, Tc - casting temperature at the casting/die interface, Td - die temperature at the casting/die interface.

From the above equation, it is observed that to enhance the heat transfer, either the variable h or $(T_c - T_d)$ should be increased. If the die, sleeve used in the casting process is made of a material having high thermal conductivity, then h will be increased, which will accelerate the rate of heat transfer and reduces the solidification time. During this investigation, amongst the various die, sleeve materials selected, the thermal conductivity of copper is several times higher than other die sleeve materials. Due to this, the solidification time was so less in the copper die sleeve, both at normal load and at the higher squeeze pressure condition. This leads to the faster rate of cooling that results in a fine grain dendrite structures with pronounced casting properties compared to other die sleeve materials. The stainless steel being a poor

thermal conductor produces the least mechanical behavior for the same process parameters.

Abrasive particles in the Si-based aluminum alloy induces a self-polishing effect and thereby reduces the dimensional accuracy of the Die over a cyclic run. The application of applied pressure in squeeze casting reduces the life of the die used. By the use of die, sleeve insert, the frequent replacement of the die becomes unnecessary in the industry to maintain the dimensional accuracy of the die/casting. Copper dies affects the casting quality due to thermal expansion, surface roughness, sticking to the casting in the die and also the cost of the die becomes higher when compared to other commercially used die materials. However, the above defects can be overcome by using copper die sleeve inserts. Couple the effect of copper die, sleeve insert and optimum squeeze casting process parameters yields sound castings.

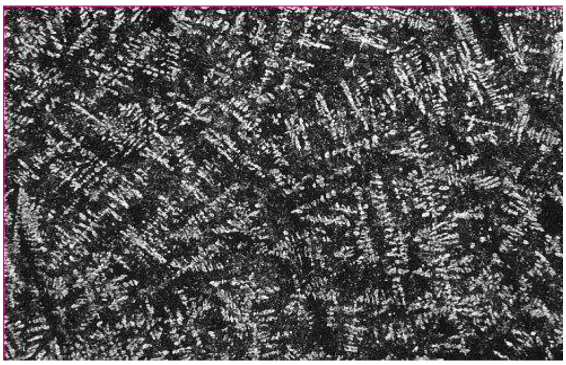
Table 2 Solidification Time taken by Different Die Sleeves

Squeeze Pressure(N/mm^2)	Solidification Time in Seconds			
	Copper	Cast iron	Die steel	Stainless Steel
70	18	21	23	31
105	12	19	21	28
140	8	17	17	24

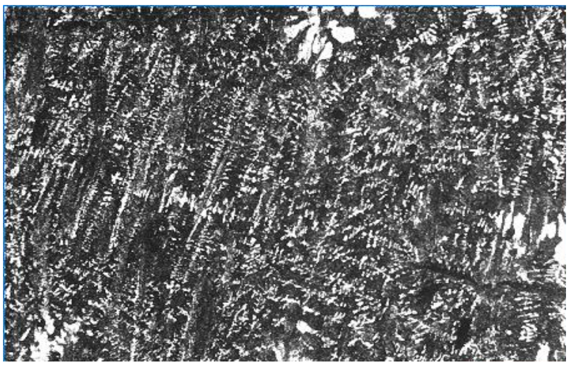
From Figure 4 & 5, it can be observed that, for the same squeeze casting process parameter, copper die sleeve yields higher UTS and Hardness when compared to other die sleeve material in the study. Table 2 shows the solidification time for different die sleeve material.

Effect of Process Parameters on Dendritic Arm Spacing (DAS)

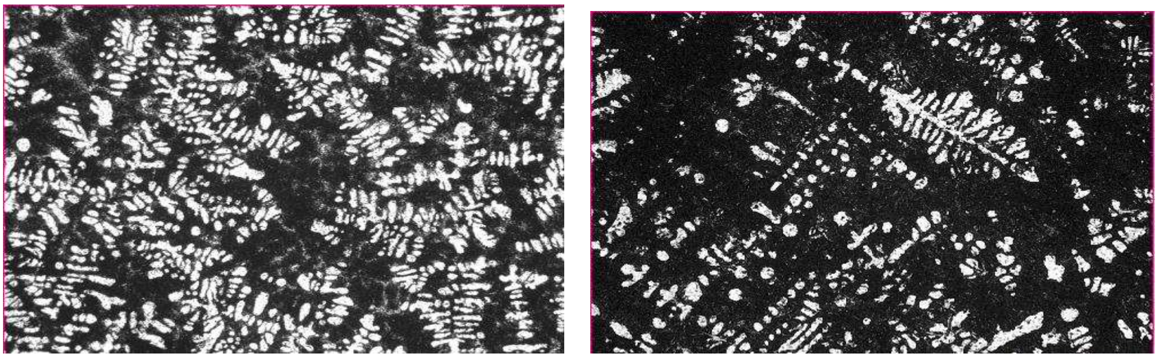
Figure 6 (a)-(d) shows the microstructures of the A413 alloy solidified under different squeeze pressures, which accelerate the formation of the dendritic structure of the castings and it was studied through a metallurgical microscope. The quantitative metallographiy analysis shows that microporosity and other defects are eliminated significantly with the increase in applied squeeze pressure. The microstructure of the cast samples consists of white regions of (α-Al) alpha aluminum dendritic in the black areas of (α-Al + Si) eutectic matrix. The dendritic branches act as the load carrying member in the matrix. By the refinement of dendritic branches, there is a significant improvement in the mechanical properties of the castings. The copper sleeve casts sample of the A413 alloy at squeeze pressure 140 MPa with die preheating temperature of 225°C and melt temperature of 725°C reveals a fine dendritic structure and shows superior mechanical properties than others. The coarse dendritic structure was formed in the cases of other die sleeves respectively, due to delay in solidification.



(a)



(b)



(c) **(d)**

Figure 6: Microstructure at Squeeze Pressure 140 MPa, Die Preheating Temperature 225°C and Melt Temperature 725°C (a) Copper Sleeve (b) Cast Iron Sleeve (c) Die Steel Sleeve (d) Stainless Steel Sleeve at 100x Magnification.

CONCLUSIONS

A413 aluminum alloy castings with different squeeze pressures die pre-heating temperature and melt temperature for four different die, sleeve materials were successfully fabricated by squeeze casting route. Experiments revealed that squeeze pressure of 140 MPa, a die pre-heating temperature of 225°C and melt temperature of 725°C yield better responses due to rapid solidification and elimination of microporosity. In cyclic run the dimensional accuracy of casting is affected due to self-polishing effect, leading to a frequent change of dies. Die sleeve inserts help us to overcome the frequent change of dying. The castings made from copper die, sleeve were superior in properties when compared to those made from another die sleeve. The copper die, sleeve has a higher heat transfer coefficient and it accelerates the heat transfer and reduces the solidification time. In experimentation, the sound castings with higher mechanical properties were made from copper die, sleeve at optimum process parametric condition due to their coupled effects. The fine dendritic structure is one of the methods for deciding grain fineness of casting, fine grains with pronounced mechanical behavior were obtained by using copper die sleeve inserts among the various die sleeve materials used.

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